# Impurity seeding with dust injection in tokamak edge plasmas

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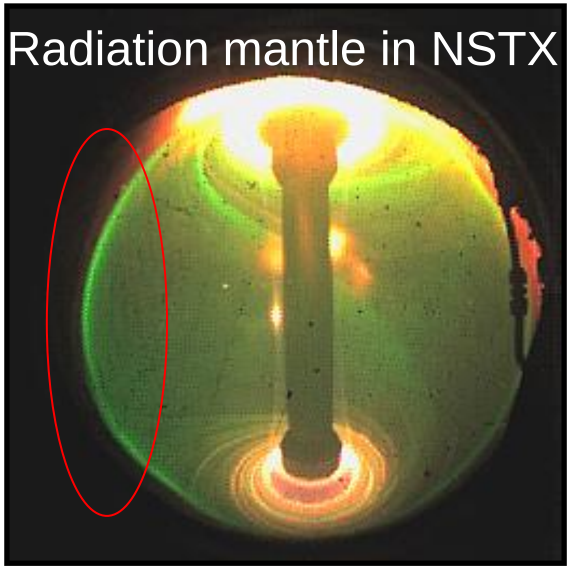
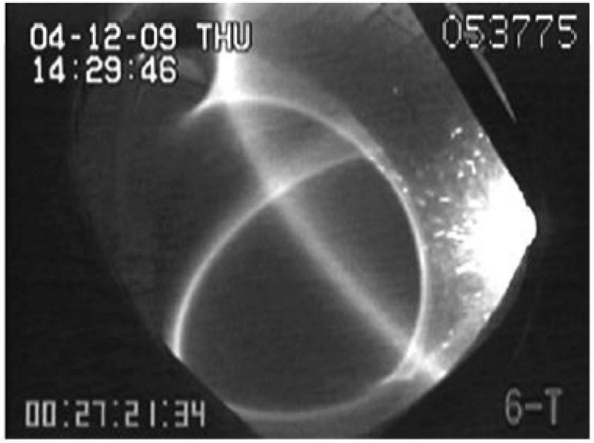
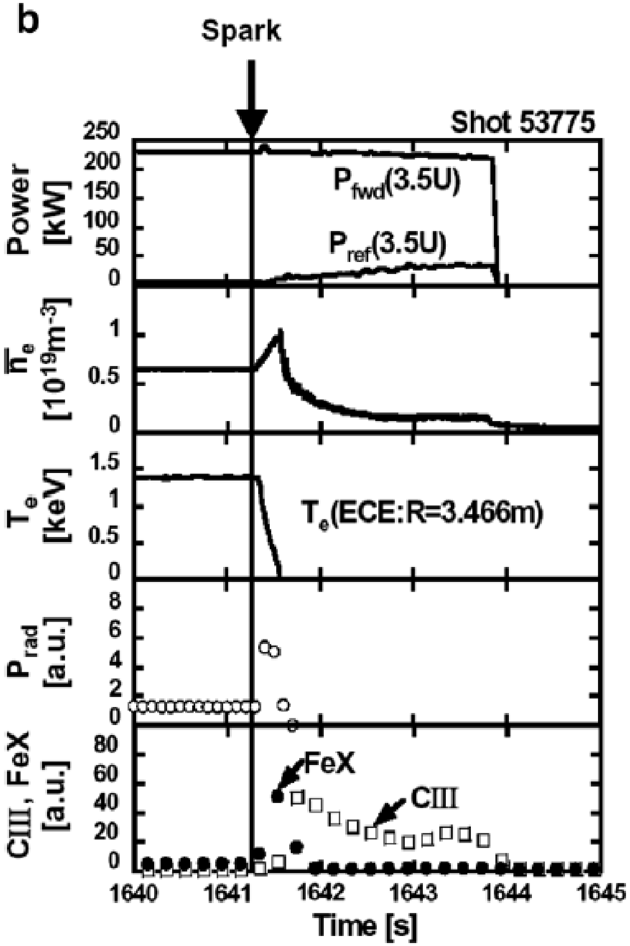
# Motivation

- Recent experiment demonstrate that dust may have significant impact on edge plasmas
- Can dust injection be used for edge plasma control instead of gas impurity seeding?




Dust spark in LHD




Saito K, et al., *J. Nucl. Mater.*, vol. 363-365, p. 1323, 2007.
D.K. Mansfield et al., PSI-19, San Diego, CA 2010 (to be published J. Nucl. Mater.)

# Motivation

- Why to inject dust?
  - Many low-Z elements (Li, Be, B, C) are solid  under normal conditions
  - Due to large inertia and very small charge-to-mass ratio dust transport is very different from conventional impurity transport
  - Additional control is allowed by variation of dust/droplet size and speed

# Outline

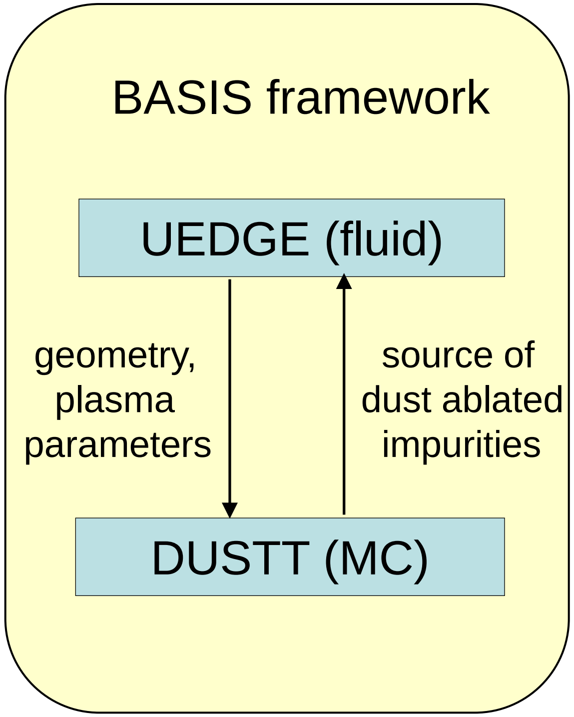
- DUSTT/UEDGE coupled code
  - Coupling scheme
  - Code validation using 3D reconstructed dust trajectories

- Dust injection in ITER
  - Divertor impurity radiation profiles
  - Divertor plate heat load
  - Effects on edge plasma stability
  - Dust vs gas injection comparison at different locations

- Modeling of lithium dust injection in NSTX
  - Dust impact on pressure gradient

# DUSTT/UEDGE coupled code

- DUSTT solves coupled dust dynamics equations including temporal evolution of dust charge, temperature, mass, and radiation
- The DUSTT code operates with plasma parameters simulated with multi-fluid edge plasma transport code UEDGE
- The statistical averaging over an ensemble of test dust particles is used to obtain dust profiles and impurity source from ablated dust
- DUSTT/UEDGE are iteratively coupled for self-consistent modeling of dust impact on edge plasmas
- Present modeling is limited to 2D toroidally symmetrical plasmas

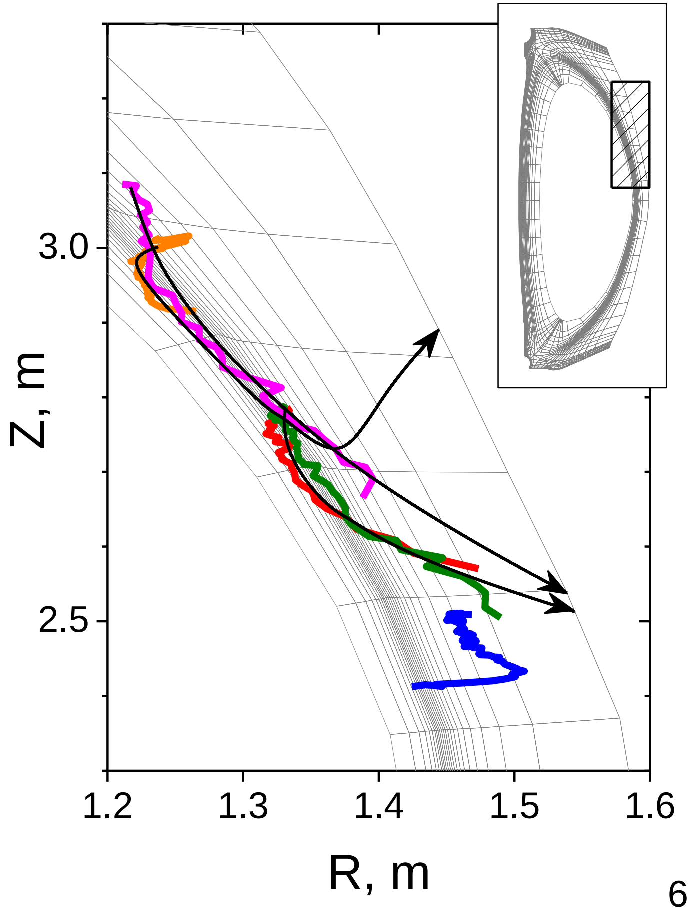


# Code validation

- The experimental trajectories are compared with the DUSTT simulated ones using plasma parameters modeled with UEDGE

| Experiment | Modeling |
|---|---|
| dust speeds ~10-100m/s | matched for dust sizes 10-20μm |
| Li dust lifetime ~10ms, some grains can reach separatrix | reproduced with introduction of heat flux reduction factor (~50) approximating dust shielding by ablation cloud |
| dust grains with opposite toroidal flight directions are observed, some grains change toroidal direction (curvature ~few cm) | shear plasma flows in SOL with Mach~1 can cause change in toroidal flight direction in near separatrix regions |

Li dust trajectories in NSTX

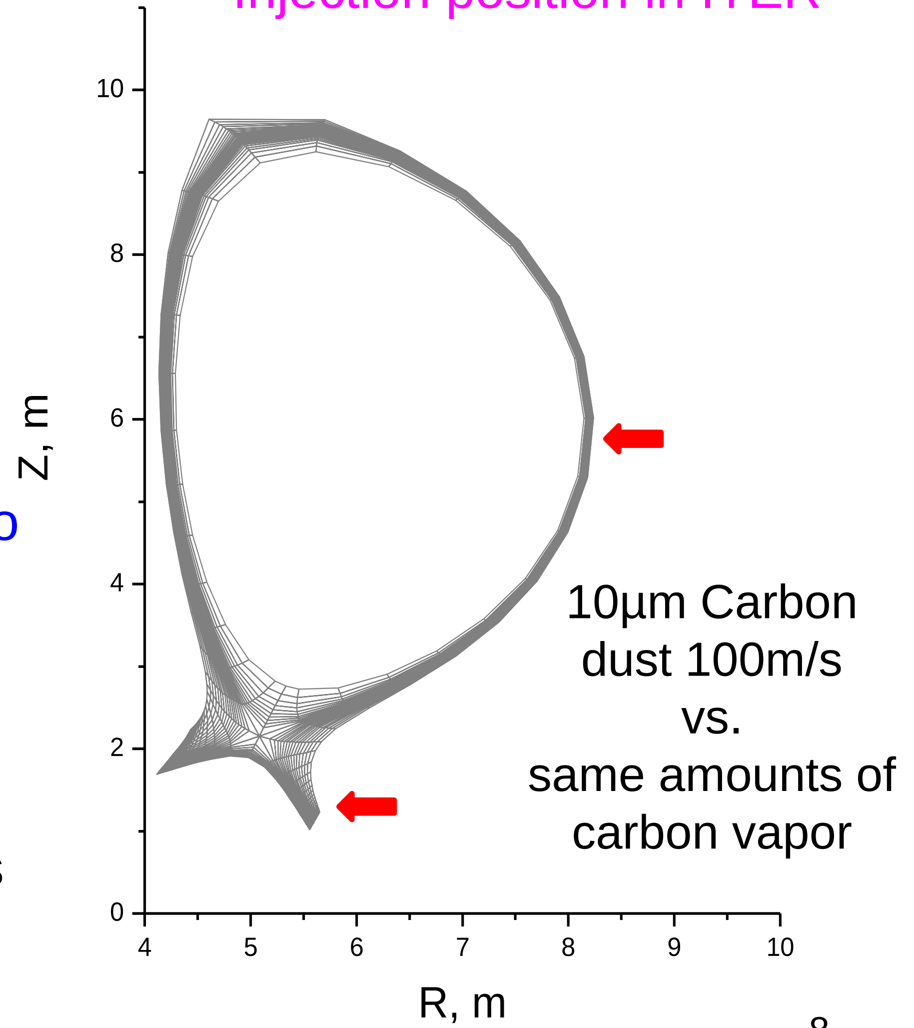


# Dust injection in ITER

# Modeling of Carbon dust injection in ITER

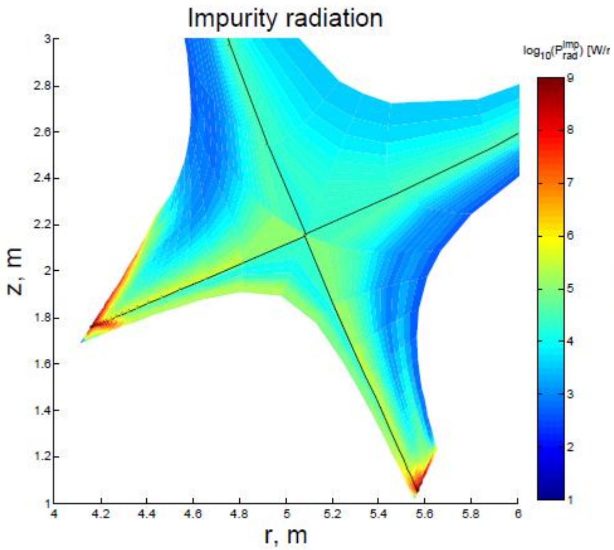
- 10μm carbon dust is injected in the outer midplane and outer divertor with radial speed 100m/s
- Equivalent amounts of carbon atomic vapor iss injected at the same locationbs
- Core $D^+$ density is $6.0 \times 10^{13} cm^{-3}$
- Divertor plates are carbon with recycling coefficient set at close to 1.0 for hydrogen (high-recycling regime) and 0.01 for carbon impurities
- Core heating power 100MW
- Carbon dust shielding factor for is set ~10

Simulated dust/gas Injection position in ITER

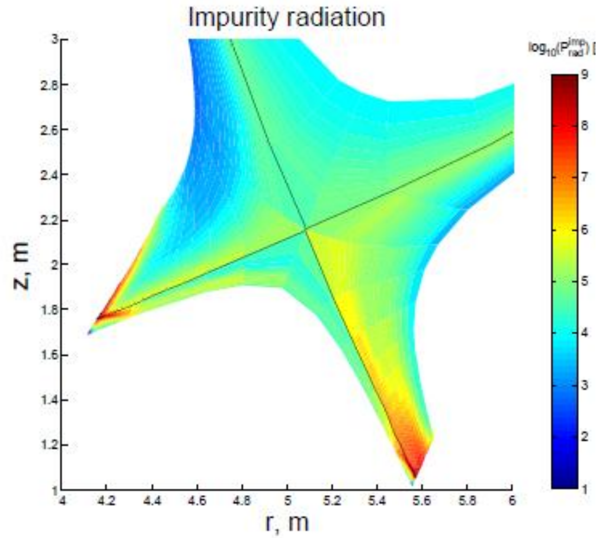


# Impurity radiation in ITER divertor

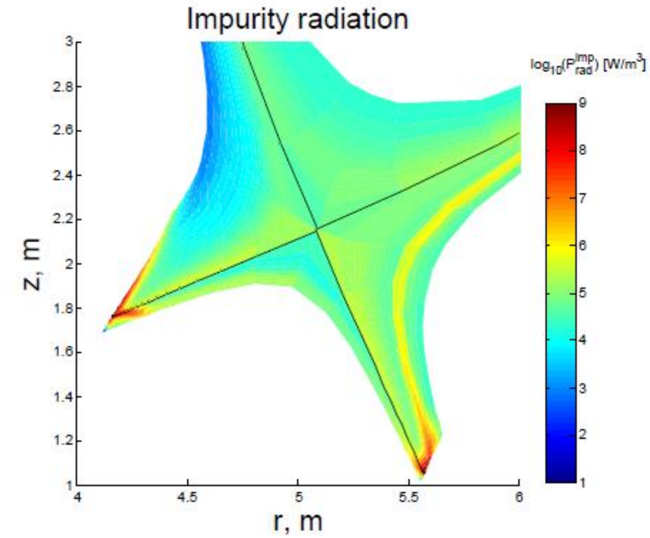
No seeding




Dust injection



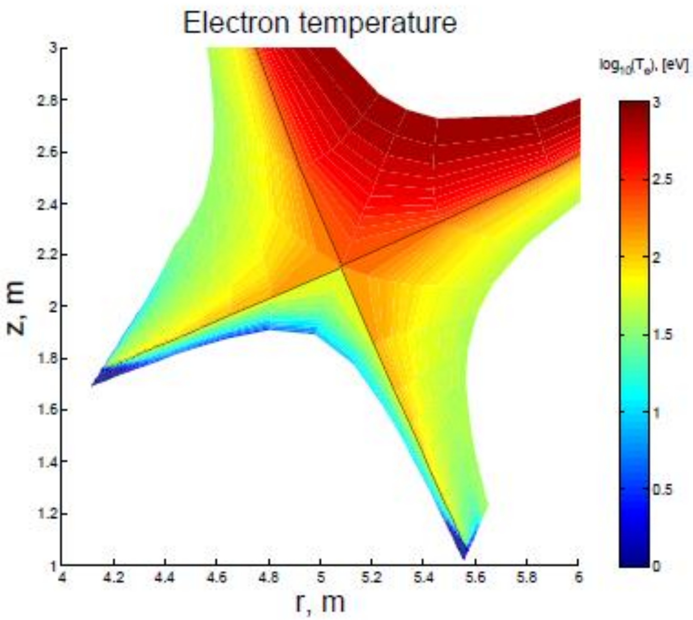

Gas puffing



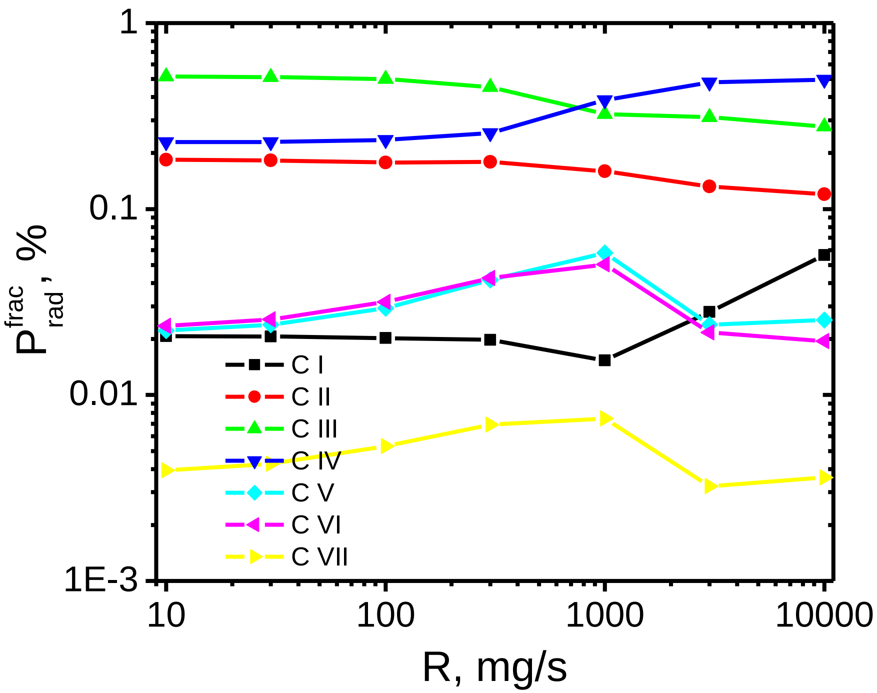

- Impurity injection in diveror region with rate 1g/s ($5x10^{22}$ atoms/s)
- Dust injection significantly increases impurity radiation power losses in a large divertor volume across the SOL
- Gas radiation pattern differs significantly from the dust injection case, forming radiation mantle
- Inner divertor radiation is less affected by dust injection

# Dust impurity radiation in ITER divertor

Electron temperature

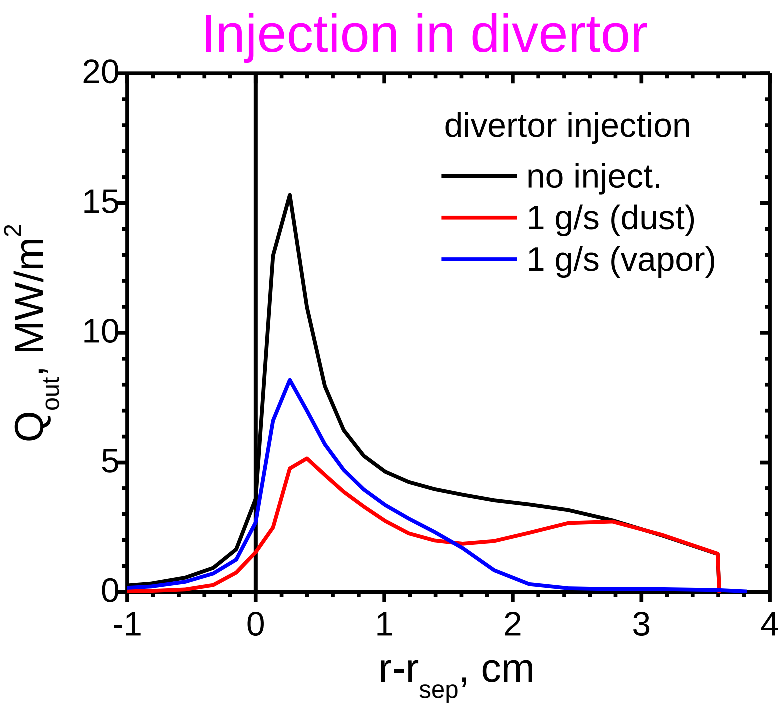


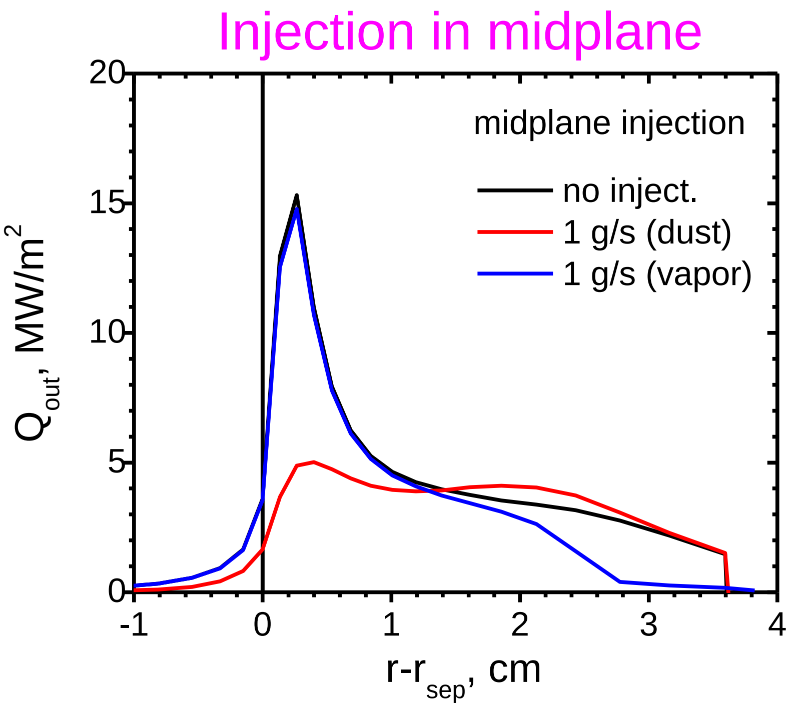

Radiation fractions




- significant amount of radiation in the dust injection case comes from hot plasmas (up to ~100eV) near separatrix
- CIII, CIV, and CII radiation dominates
- non-coronal effects may play important role in radiation of dust originated impurities

# Outer divertor plate heat load

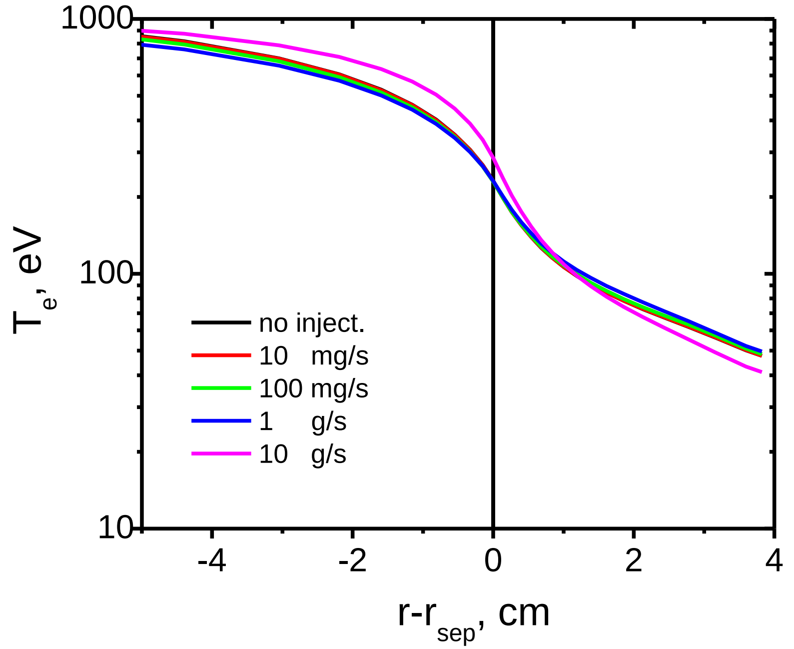


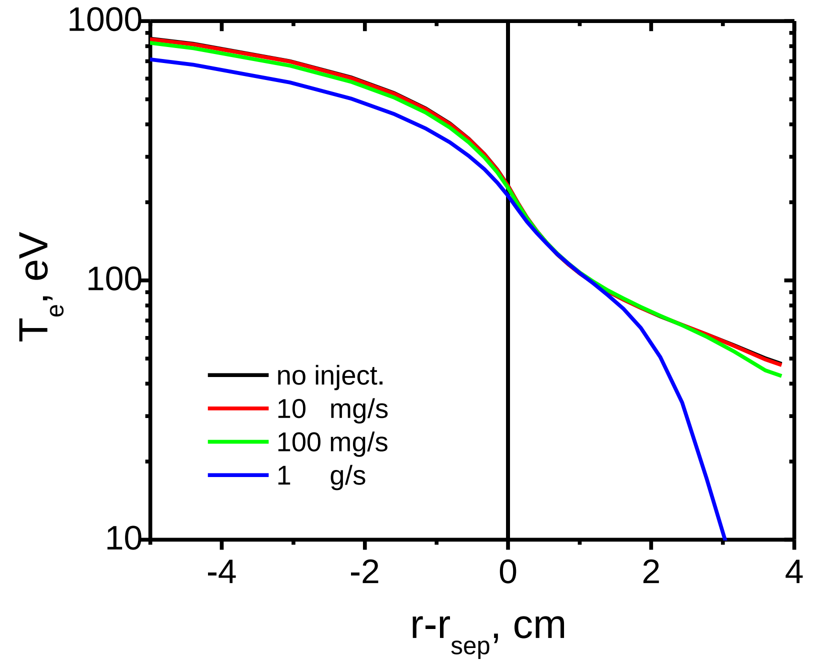

- The reduction in the peak heat load due to dust injection in both divertor and midplane cases, as compared to unseeded case, is ~3 fold from 15MW/m$^3$ to tolerable 5MW/m$^3$ level
- vapor results in ~2 fold reduction of the peak divertor heat load only when injected in the divertor region

# Electron temperature at midplane

Dust injection



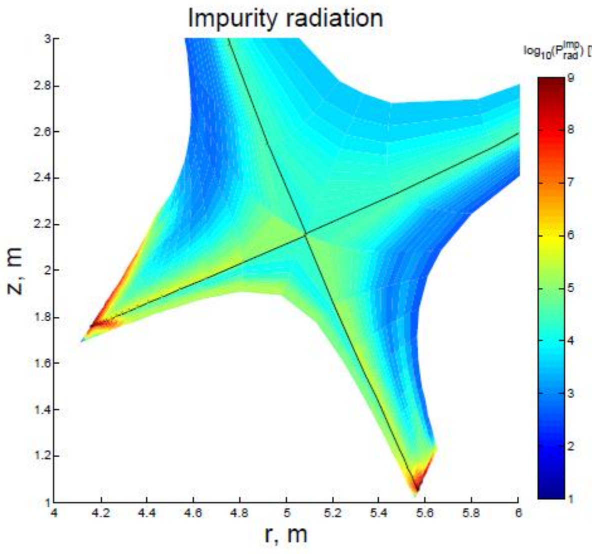

Gas puffing



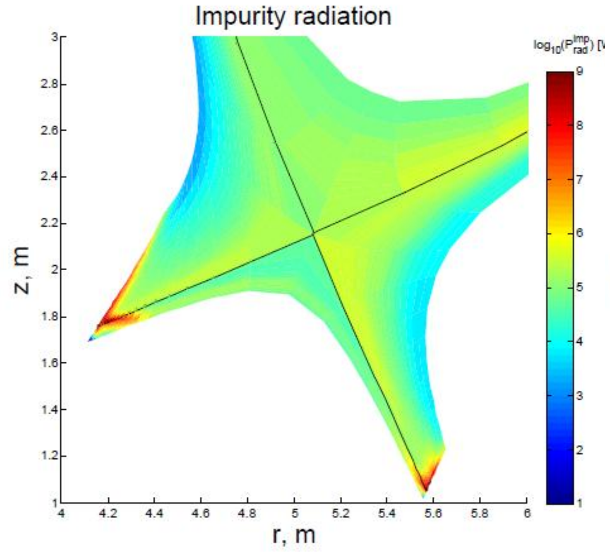

- Midplane plasma temperature is weekly affected by dust injection in divertor for rate up to ~10g/s
- Gas injection with rates ~1g/s leads to significant far SOL cooling

# Impurity seeding in ITER midplane

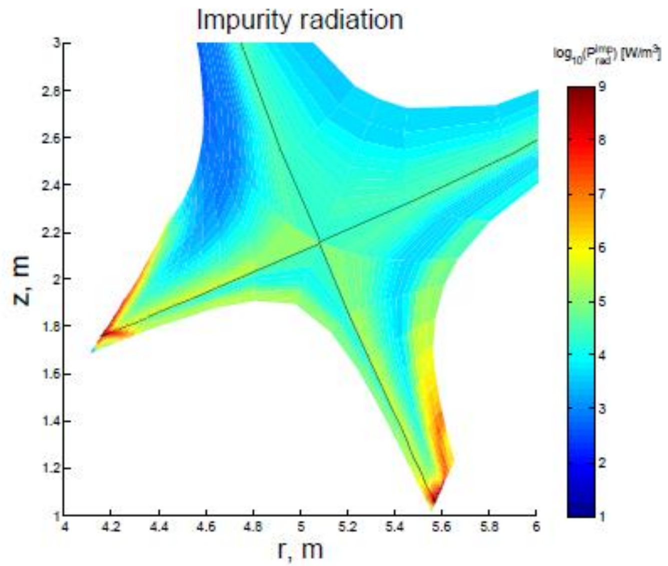
No seeding




Dust injection

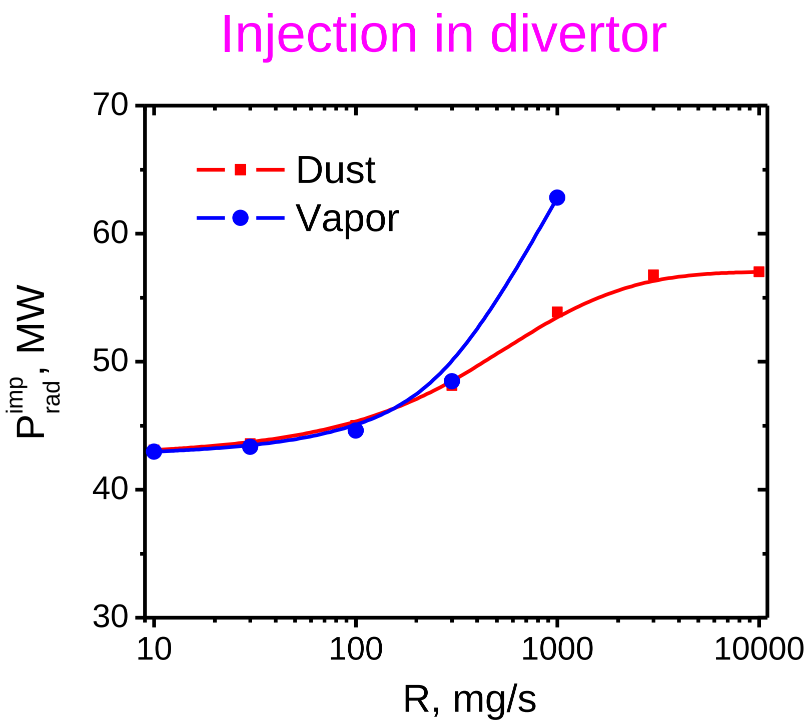


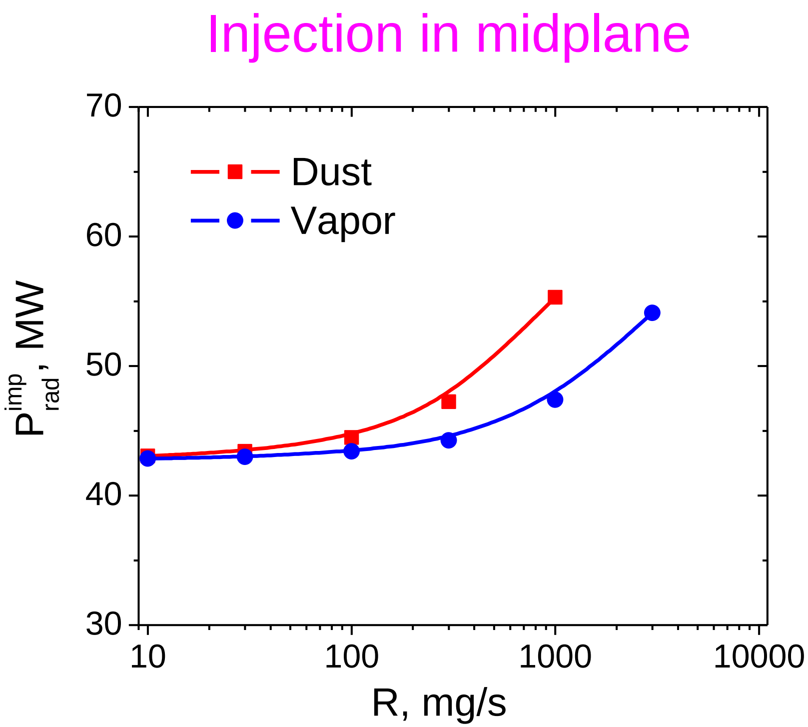

Gas injection




- Gas radiates in divertor mostly close to the wall
- Dust penetrates deeper into SOL plasma at midplane and significantly increases impurity radiation in near separatrix region

# Total impurity radiated power in ITER

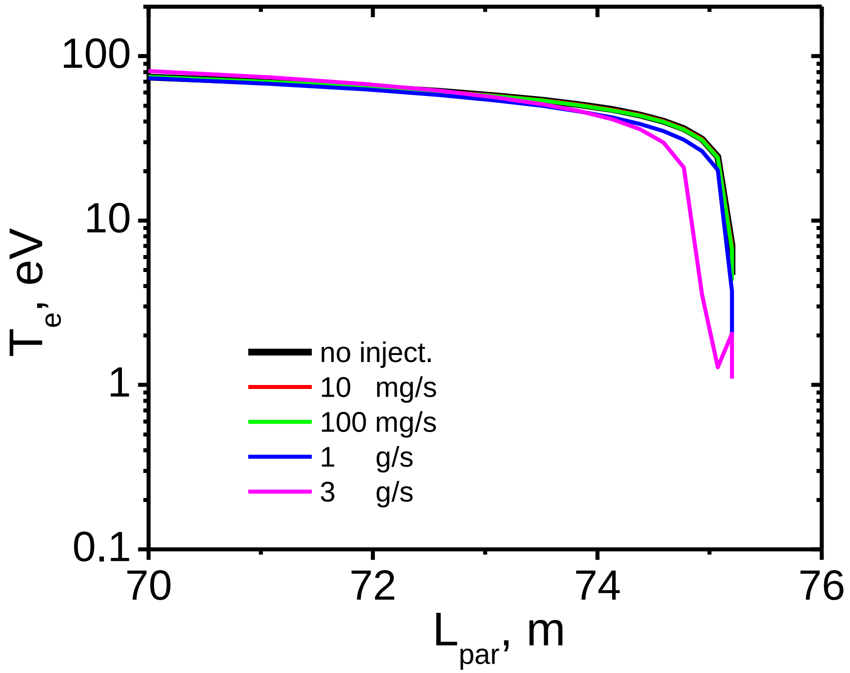


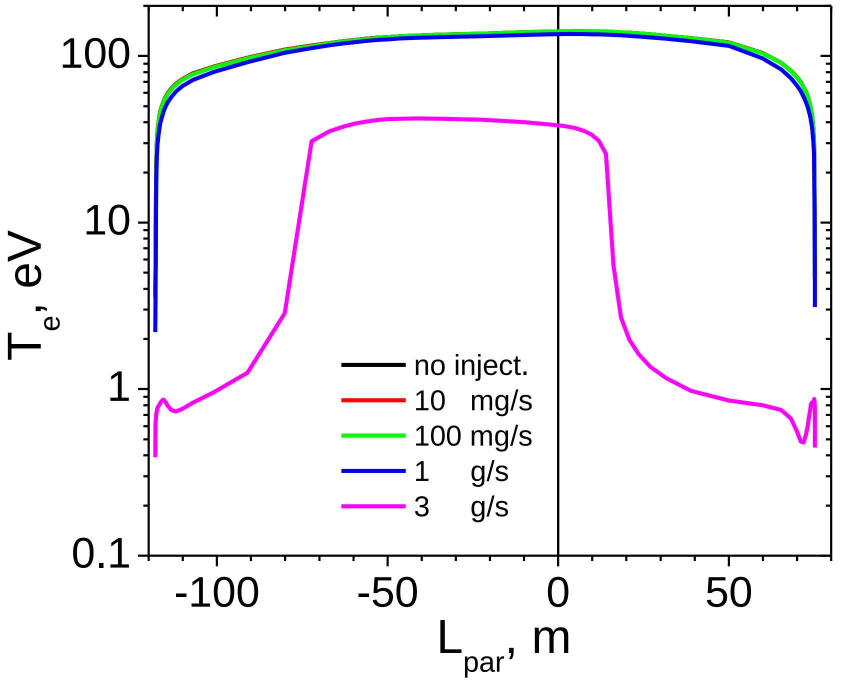

- In all simulated cases, except dust injection in divertor region, discharge terminated, when ~10g/s is injected resulting in more than ~60% of impurity radiated power fraction
- radiation of dust seeded impurities in divertor region tends to saturate at a level below one leading to development of divertor thermal instability

# Parallel temperature profiles

Dust injection in divertor




Dust injection in midplane



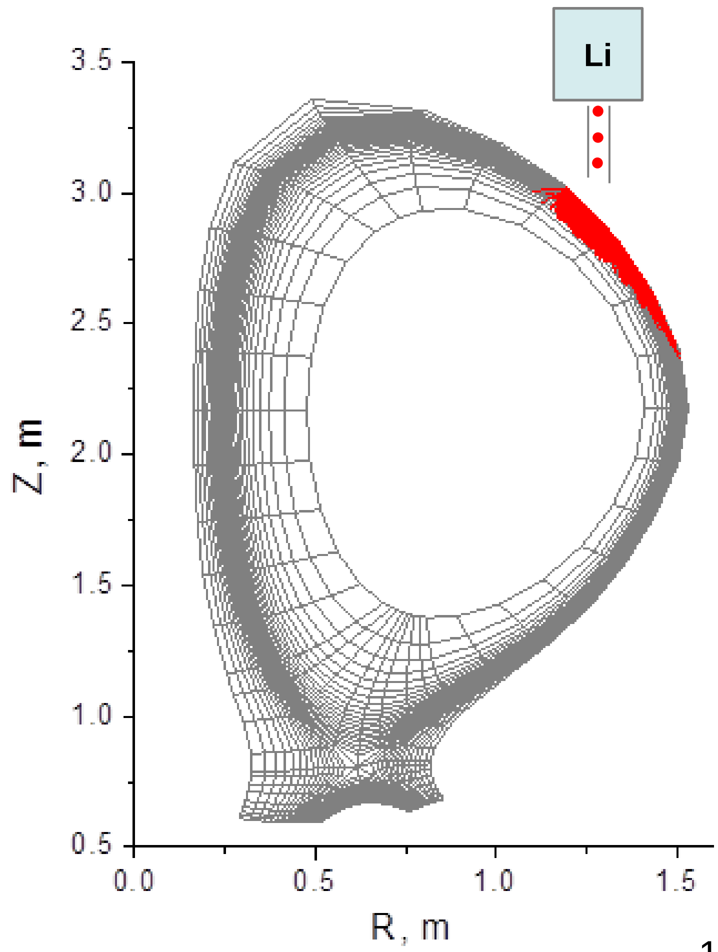

- Parallel temperature profiles are shown along a magnetic field adjacent to separatrix
- Detached divertor regime preceeds discharge termination in midplane dust injection case

# Dust injection in NSTX

# Modeling of Li dust injection in NSTX

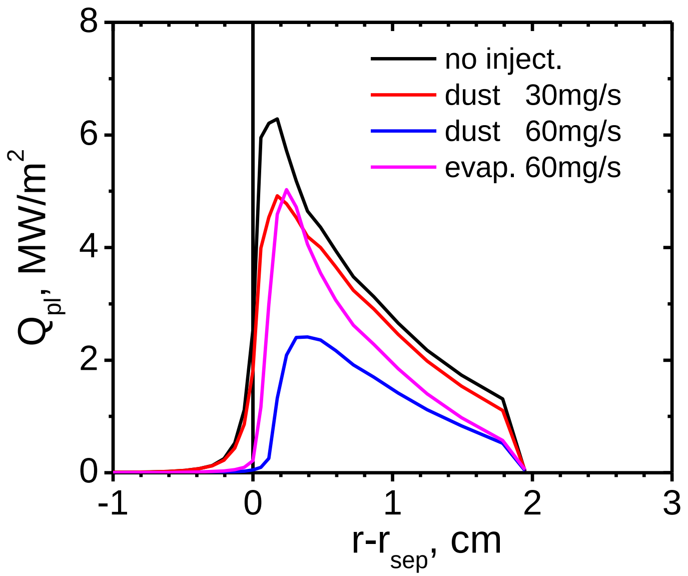
- NSTX L-mode LSN configuration is modeled
- ~20μm radius Li dust is injected in the upper outer poloidal position
- Dust hit the plasma with average speed ~5m/s and with shifted downward cosine angle distribution relative to vertical direction
- Divertor plates are assumed to be covered with Li film with recycling coefficients set at 0.8 for D and at 0.5 for Li (low-recycling regime)
- Core $D^+$ density is fixed at $5.1\times10^{13}$ $cm^{-3}$
- Core heating power 3MW

Configuration of modeled Li dust injection

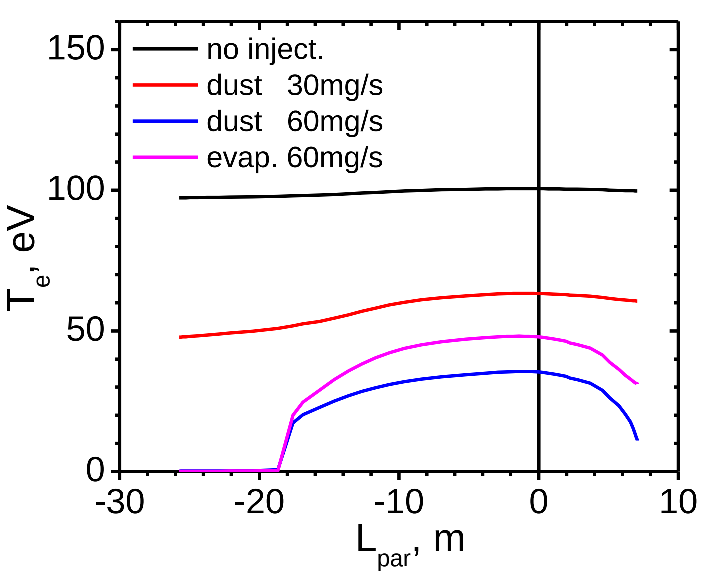


# Impact of Li dust on divertor operation

Divertor heat load profile



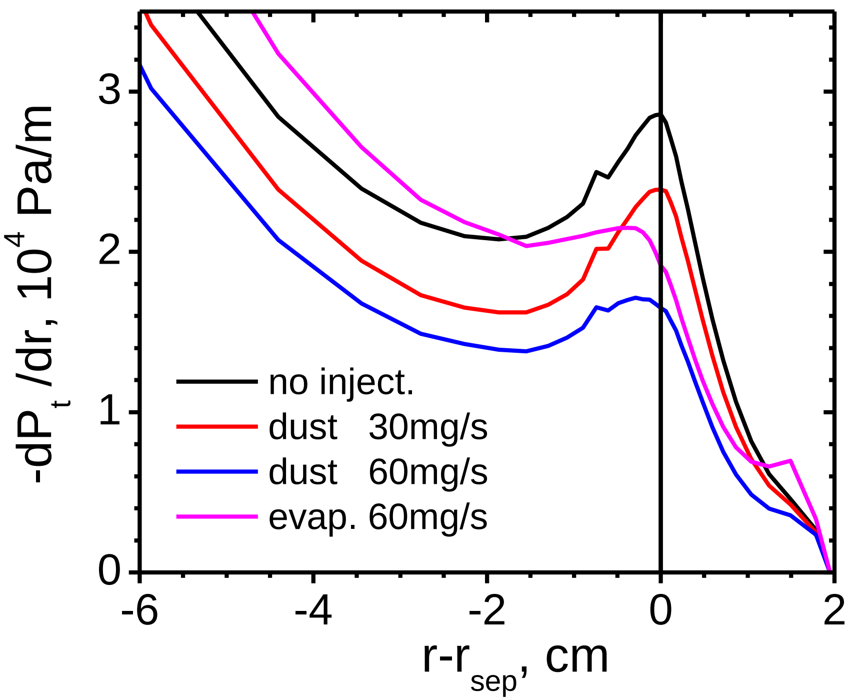

Electron temperature



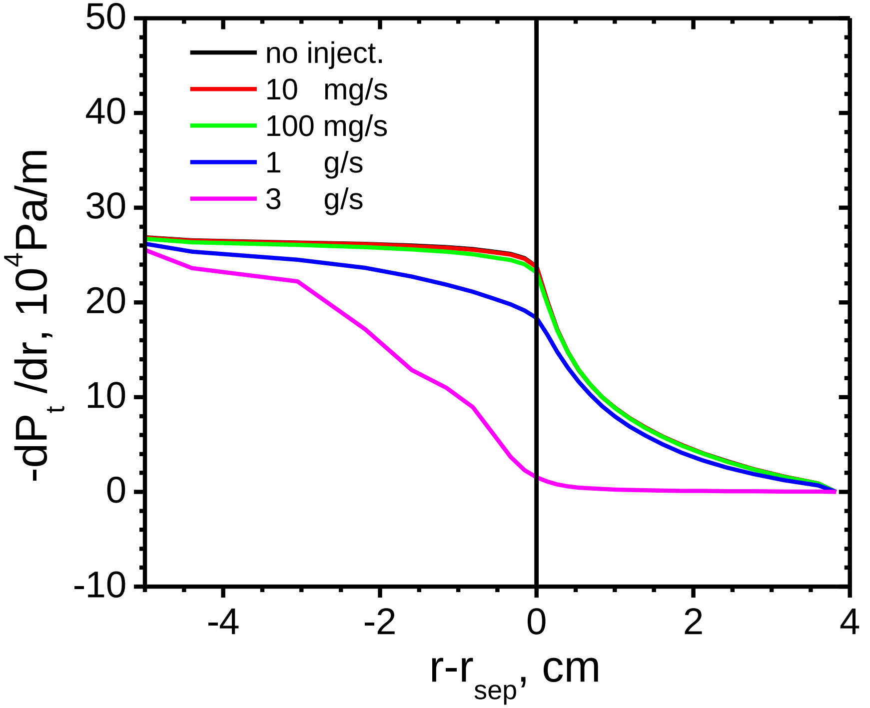

- The peak power load to the outer divertor plate is significantly reduced
- Broader heat load profile compared to gas injection
- Complete plasma detachment in the inner divertor at 60mg/s Li injection rates is developed

# Radial pressure gradient profiles for dust injection at/above midplane

NSTX




ITER




- Radial plasma pressure gradients are substantially up to ~40% reduced in the edge
- Peeling/ballooning stability of the edge plasma can be improved, suppressing anomalous transport and ELM formation

# Summary

- The coupled DUSTT - UEDGE code allow self-consistent modeling of dust transport and impact on the edge plasmas

- The DUSTT/UEDGE code has been validated using 3D reconstructed dust trajectories measured on NSTX

- Dust injection with rates ~ several 10mg/s in modern tokamaks and ~1g/s can significantly affects edge plasma parameters, transport and stability

- Dust injection is more effective in reduction of the divertor peak heat load as compared to gas impurity seeding

- Radiation of impurities seeded by dust injection in divertor region tends to saturate leading to thermal stabilization of divertor